Final Report

on the Four-Month Extension of MURI contract N00014-96-1-1223

"High Power, Broadband, Linear, Solid State Amplifier"

For the period:
September 1 – December 31, 2001

Sponsored by:
Office of Naval Research
John Zolper, Monitor

Submitted by:
Lester F. Eastman, P.I.
Cornell University
School of Electrical and Computer Engineering
425 Phillips Hall
Ithaca, NY 14853-5401
TEL: (607) 255-4369
FAX: (607) 255-4742
e-mail: lfe@iiiv.tn.cornell.edu

January 2002

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)

2. REPORT DATE
Jan. 30, 2002

3. REPORT TYPE AND DATES COVERED
Final 4 months extension (9-1-12/31/2001)

4. TITLE AND SUBTITLE
High power, broadband, linear, solid state amplifier

5. FUNDING NUMBERS
MURI N0001-96-1-1223

6. AUTHORS
Lester F. Eastman, contract P.I.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cornell University, Elec. and Computer Eng.
425 Phillips Hall, Ithaca, NY 14853-5401

8. PERFORMING ORGANIZATION REPORT NUMBER
none

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research, Dr. John Zolper
800 N. Quincy Street, ONR 312, Room 607
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
none

11. SUPPLEMENTARY NOTES This MURI contract was scheduled to end on August 31, 2001. However, as prime contractor, Cornell had not yet met its obligations on cost sharing. A request was made, and approved, for a no-cost extension to December 31, 2001, to meet its obligation with industrial grants.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
General available to the public

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This report only covers the four months extension period of this contract. The summary report of the earlier five year effort is attached.

During the extension period the undoped AlGaN/GaN material structure was modified to include a thin AlN layer at the heterojunction. A 15.3 Å layer was optimum for confinement of carriers and low ohmic contact transfer resistance. HEMT's with this structure showed promise, with 1.5 A/mm channel current, but the .30 μm gate broke down at pinch-off with 25 V drain-source bias. Without the AlN layer, HEMT's with 1.2 A/mm channel current could be biased to drain-source voltage of 45 V, and reached new state-of-the-art performances of 11.7 W/mm at 10 GHz with .3 μm gates, and 2.32 W/mm at 35 GHz with .12 μm gates.

14. SUBJECT TERMS
microwave transistor, Gallium nitride, MBE OMVPE and bulk growth power combining circuits

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-1
298-102

I. Introduction

During the period from September 1 – December 31, 2001, effort continued on this MURI contract, after an approved extension, using unrestricted grants from industry. This report briefly covers the highlights of the program during this period. The two key areas covered are the undoped materials growth, and the AlGaN/GaN HEMT performance.

II. Materials growth and characterization

Using the flow modulation epitaxy mode of OMVPE growth in the Cornell vertical barrel reactor, the undoped AlGaN/GaN HEMT wafers were grown. The growth was on SiC substrates, at a substrate temperature of 1040° C and a pressure near 10% of atmospheric pressure. Sequentially, an $Al_xGa_{1-x}N$ nucleation layer, ~ 200 Å thick, with x in the .05 - .10 range, then an AlN sub-buffer, 2,000 Å thick, then the GaN buffer/channel layer, and finally the undoped $Al_yGa_{1-y}N$ top barrier layer were grown. The standard top barrier layer has $.30 < y < .40$, with a thin AlN layer on top of the GaN buffer/channel layer in some cases. The thickness of this layer was determined to be near optimum when it was 15.3 Å (6 molecular layers), with 7.65 Å being too thin, and 22.95 Å being too thick. When only 7.65 Å thick, electrons tunneled through it, under a small positive gate bias, not allowing the required confinement to the channel. When it was 22.95 Å thick, the annealed ohmic contact transfer resistances at the source and drain were substantially higher than the .3 - .50 Ω-mm usually obtained. In order to control the thickness, growth rates were calibrated in terms of the number of molecular layers of AlN deposited during each rotation of the susceptor (in and out of the TMA region), and then rotations were counted to achieve the specific AlN thickness. One wafer was grown with 200 Å of $Al_{.39}Ga_{.61}N$ as the top region of the barrier, and 15.3 Å of AlN between that region and the GaN buffer/channel region. The average 2DEG electron sheet density in that wafer was 1.6 x $10^{13}/cm^2$. This electron sheet density was appreciably higher than the 1.0 – 1.2 x $10^{13}/cm^2$ present in our usual, high-performance wafers.

III. AlGaN/GaN HEMT device fabrication and testing

The HEMT's were fabricated by our standard process of annealed ohmic contacts yielding .3 - .5 Ω-mm contact transfer resistance, and with mushroom-shaped cross-section gates with .3 μm and .12 μm gate footprints. A center-fed, single 100 μm wide device yielded a new state-of-the-state of CW power density of 11.7 W/mm with 42% power-added efficiency at 10 GHz using the .3 μm gates. HEMT's with .12 μm gates yielded the state-of-the-art of CW power density of 2.32 W/mm with 22% power-added efficiency at 35 GHz.

Experiments at 10 GHz, with 10 channels, each with .3 μm x 150 μm gates were done with different gate pitches. Our usual gate pitch of 50 μm was used as a reference. If the pitch was raised to 75 μm, the power-added efficiency and the output power rose by a few percent. When the pitch was raised to 100 μm, the power-added efficiency dropped by 25-30%, even though the channels should be running cooler with such large pitch. The effect of phase differences in the output currents from the different channels was analyzed to explain this efficiency difference. It was then determined that the total gate and drain phase increment between currents in adjacent channels was 33° for 10 GHz operation, and 50 μm pitch. This phase difference rises linearly with frequency, and as the square root of the pitch.

Devices made with the 15.3 Å AlN layer between the $Al_{.39}Ga_{.61}N$ barrier and the GaN buffer/channel layer were also tested. They yielded a high (1.5 A/mm) normalized channel current, but had a gate breakdown at pinch-off if the drain-source voltage exceeded 25 V. The high electric field under the gate, due to the high gate-source pinch-off voltage, coupled with the contribution to this electric field by the drain-source bias, appears to be the cause of this gate breakdown, based on a simple tunneling analysis.

Finally, monolithic VCO and narrow-band amplifiers were fabricated and given preliminary tests. The Varactor for the VCO used a HEMT structure. The narrow-band amplifier used on-chip second harmonic tuning, which experimentally missed the design frequency that would be twice the 10 GHz fundamental frequency design, in this first test.

III. Student employment and technology transfer

Students trained on this MURI have taken positions at Raytheon, BAE North America, Lucent Bell Laboratories, CREE, ATMI, Motorola, H.P., Nova Crystals, EMCORE, and RF Nitro Communications. The latter, located in Charlotte, NC was a new Cornell-based start up marketing AlGaN/GaN HEMT wafers. It has recently been purchased by RF Micro Devices and continues the marketing of materials and devices. Various aspects of the Cornell AlGaN/GaN HEMT technology are also being transferred to Northrop Grumman, Raytheon, GE/CRD, BAE North America, EMCORE, RF Micro Devices, Motorola, Triquint, and Rockwell.

V. Conclusion

This report ends the present contact. Work continues funded by several small grants from industry. In general, the program was highly successful, achieving reproductible high quality material and fabrication methods, including the invention of the use of Si_3N_4 on the exposed surface of the device semiconductor, to stop the current slump from surface state charging. State-of-the-art CW power density, about an order of magnitude higher than that of other materials resulted, and the students trained, along with the key technology areas, are being transferred to industry. A copy of the summary final report, submitted earlier after the conclusion of the initial five-year MURI effort, is attached.